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by

A. A. Rumyantseva, V. I. Yevseyev

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BIOMECHANICS OF THE ATLANTO-OCCIPTAL AND ATLANTO-AXIAL JOINTS' LESIONS

A. A. Rumyantseva, V. I. Yevseyev

The biomechanics' specificity of the atlanto-occiptal and atlanto-axial joints is conditioned both by their function and their anatomical structure. Inasmuch as from the point of view of anatomy and the function, these joints have been described in details; their biomechanics both under conditions of laws and pathology remains insufficiently examined. A detailed analysis of the biomechanics of the atlanto-occiptal and atlanto-axial joints has allowed to clarify the reasons for the lesions of this part of the vertebral column as well as has resulted in obtaining a precise diagnosis and determining a proper treatment.

The method of the mathematical modeling has been applied to the anatomical preparations and X-ray pictures of the upper part of the cervical region of the vertebral column in order to determine the nature of force resolution in the atlanto-occiptal and atlanto-axial joints on three planes, namely - on the principal plane, on the axial plane and on the horizontal one under the condition of the static load which is caused by the action of the head weight as well as by the neck muscles and by the directed action of the traumatic forces.

It has been confirmed that under regular conditions when taking into consideration the physiological lordosis, the principal acting forces are the following ones: the P_2 force representing the head weight; the P_1 force representing the neck muscle; and the P' and P" forces representing the forces of the static load of the atlas which are conditioned by the above mentioned forces (see Figure 1). When there exists the head lever equilibrium

($P_1 \cdot a = P_2 \cdot b$ according to L. P. Nikolayev) and if to accept that the head weight designated as $P_2=4.9$ kg, $a/b=0.4$, then the ($P'+P''$) forces of the static load will amount to 6.8 kg.

On the principal plane, the forces of the static load (P' and P'') are transmitted from the atlanto-occiptal joints onto the central axis of the vertebral column's neck part in the form of component force designated P_v (see Figure 1a) which is vertically directed.

On the axial plane (Figure 1b), when the atlas is located horizontally, the P_v force due to its physiological lordosis is directed toward outside from the central axis of the vertebra's trunk, and it can be considered according to two constituents: the P_0 one which represents the force of the axial load being equal to $P_v \cdot \cos C$ and P_s representing the displacing force which is equal to $P_v \cdot \sin C$ and which is directed towards the rear and balanced by the force of the transverse ligament of the atlas designated as R. It has been confirmed that under the conditions of the physiological lordosis of the average degree at the $C=5-10°$ angle, the tension force of the atlas transverse ligament (designated as R) amounts to 0.8-1 kg. Such a permanent action of this force (in the author's opinion) retains the determined degree of the transverse ligament tension and conditions its absorption role.

The analitical functional characteristics of the atlanto-axial joint are based on lack of the joint surfaces' congruence. Under the condition of the horizontal equilibrium of the first cervical vertebra, the contact between the atlases and the axes occurs only at the "top of the joint" which results in rising the joint angles; namely - the A angle which is open towards the front and the B angle which is open towards the rear. Due to the above-mentioned, the inclination of the first cervical vertebra as against to the second cervical vertebra amounted to the A angle in the direction of the front and to the B angle in the direction of the rear. According to Ingelmark (citing V. G. Selievanov and M. N. Nikitin) the amplitude of the frontal-rear inclinations of the atlas as against to the axis amounts to 7.5-14°.

In the horizontal view (Figure 1c) when the head is located on the principal and axial plane, the P' and P" forces of the static load are applied to the upper joint surfaces of the atlas on the M-N line, which secures the equilibrium of the atlas with regard to the axis. Since the upper joint surfaces of the atlas are located at angle β with respect to each other, angle amounting to 40°, there is a possibility to rotate the head at angle α with respect to the atlas, i.e., 28-30°. This results in displacing the condyle of the occiput bone along the joint surfaces of the atlas in the frontal-rear direction, whereas the forces of the static load fall either on the M_1-N_1 line or on the M_2-N_2 line.

Such an action of the P' and P" forces, under the full rotation of the atlas as against to the axis, disturbs the equilibrium of the location of the first cervical vertebra and causes its block. The contact of the side masses of the atlas and of the axis occurs not on the "joint top", but on the inclined parts of the joint surfaces. It is considered that the mechanism discussed appears at the extreme phases of the head rotation and represents one of the initial stages of the appearance of the rotation subluxations of the atlas.

The analysis of the biomechanical functional characteristics of the atlanto-occiptal junctions as well as these of the atlanto-axial ones has proved that the force resolution of the P' and P" static loads changes depending on the angles of the atlas inclination as against to the axis in the frontal-rear directions (Figure 2).

If the atlas is inclined towards the front (Figure 2a), then the direction of the static load forces ($P'+P''=P_V$) does not fall on the vertebral column axis, that results in increasing the P_s displacing force, and respectively, in increasing the tension force of the transverse ligament of the atlas, designated as R.

If the atlas is inclined towards the rear (Fig. 2b), then the P_s displacing force increases respectively; this force is directed towards the front and is balanced by the R reaction force of the atlas front arch.

The atlas inclination towards the front, according to the authors' observations within the regular conditions is possible to obtain up to 13° and is limited by the rear ligamental group. In case, if these ligaments are injured, the inclination angle could increase to 45° and up. The atlas inclination towards the rear under pathologic conditions is possible within significantly smaller limits, because the inclination is limited by the tension of the frontal elongated ligament as well as by the counteraction of the rear ligamental group.

In this way, the principal biomechanical specificity of the atlanto-occiptal and atlanto-axial joints under regular conditions, is based on the changes in the force resolution of the static loads in different atlas locations as against to the axis. There is no doubt that the discussed biomechanical specificity of the upper section of the neck's vertebral column represents an essential element for considering different pathological conditions, particularly when a traumatic injury factor starts acting.

For the purpose of specification of the above described biomechanical functions' influence on the kind of traumatic injuries, the traumatic mechanism has been examined. Seventy-three patients with fractures and dislocations of both upper cervical vertebras have been examined. The kind of injury and the frequency of occurence among the examined patients are presented in Table I.

Table I. Kind and frequency of injuries of upper cervical vertebras

Kind of injuries		Amount of patients
Atlas	Intertooth dislocation	16
	Interligament dislocation	6"
	Rotational dislocation	5
	Bilateral fracture of the posterior arch	5
	Cracking fracture - atlas dislocation	2
Axis	Traumatic spandilolisthesis	18
	C-2 dislocation	2
	Fracture of the axis tooth without dislocation	6
	Arch fracture	7
	Breaking away a piece from the frontal-lower edge of the trunk	6
	TOTAL	73

") In one case, besides the counterligamental dislocation, there was also the tooth fracture.

The comparison testifies of a more frequent dislocation of the atlas and the frontal displacement of the axis tooth along with the atlas arch fracture.

A typical reason of indirect trauma accompanied by the action of the vertical force causing the dislocation and fracture of the upper cervical vertebras, was a fall down on the head (e.g. from a truck with a load, when practicing gymnastics, when falling out of the car or motorcycle). Altogether there were 44 patients.

There were 10 persons in the group of divers. A load falling on the head or striking it during an automobile accident was represented by 7 patients. Two patients were hit in the head frontal part during the motorcycle ride, i.e., when the traumatic force was directed horizontally. In this case, when the blow is received obliquely, ~~strike runs indirectly,~~ which has been observed in most cases, the external force falls directly on the head in the vertical or horizontal directions.

The direct trauma has been observed only in 10 cases. The trauma represented the strike into the rear part of the neck, which means that the traumatic force was acting horizontally.

The method of the mathematical modeling has been used for the examination of joints' boimechanics; the atlanto-occiptal and atlanto-axial joints are investigated under the condition of the horizontal and vertical traumatic forces action which is presented on Fig. 3.

According to Fig. 3a, the action of the T_c vertical traumatic force causes an increase of the (P_v) total load of the neck's part of the vertebral column, and, consequently, its components (P_s and P_σ) whose magnitude depends on the inclination angle of the atlas as against to the axis.

The action of the trauma horizontal forces, shown on Fig. 3b (where the T_a is a stroke running towards the rear and the T_b is the frontal stroke), changes only the load of the transverse ligament or of the atlas frontal arch and also depends on its inclination.

When computing the loads, the G.R. Graffer and A.I. Bykowsky's data have been used. According to these data, the sudden stroke forse produces 10-fold increase, which means that the object has fallen down on the head from the 10 m height or higher, and the loading force of the neck's vertebral column (when the body weight is 70 kg) amounts up to about 700 kg. When the fall takes place from the height equal to the human body height, the loading force of the neck's vertebral column will be 90 kg, whereas when the head is hit and if its weight amounts to 5 kg, then the loading force increases up to 50 kg.

The magnitude of the P_o axial load and this of the P_s displacing force which is applied to the t ansverse ligament of the atlas and to its frontal arch at different angles of the atlas inclination, is presented in Table II.

As one can see from Table II under regular conditions, the load distribution along the Ist and 2nd cervical vertebras,is located within the range of 0.54 to 6.8 kg, which evidently does not exceed the limits of their mechanical resistance.

At the moment of ~~the~~ a direct blow to the head ~~stroke~~, e.g. against the car roof (during bouncing or rolling over) ~~as at the moment of tossing or the car's turning upside down~~, under the atlas 13 to 45^o frontal inclination, the maximum load, the atlas's transverse ligament undergo loading within 15 to 47 kilograms, which can be accountable for the intertooth or interligamental injuries.

When an object is falling onto the head from the human body height the loading of the transverse ligament increases up to 65.8 kg, whereas the axial load can amount up to 95.2 kg. It results in rising the conditions for the intertooth, ligamental and vertebral column injuries.

The maximum loads of the neck's vertebral column occur when an object falls on the head from the height exceeding the human height. Thus, when an object falls down from the 10 m height or higher under the condition of the atlas frontal inclination, the load of the frontal ligament of the tooth can increase up to 15~~0~~4 to 490 kg, and the vertebral column axial load can amount to 700 kg. Thus, by means of such axial and lateral loads one can explain the appearance of the traumatic spandilolisthesis of the axis as a result of the fracture of the axis arch base.

Table II. Load distribution along the Ist and 2nd atlas when the traumatic force acts vertically

Kind of trauma	Load forces	The atlas inclination as against to the axis			
		0^{0}	Physiological 5^{0}-10^{0}	Towards the front 13^{0}-45^{0}	Towards the rear 13^{0}-24^{0}
Regular conditions	Transverse-Axial ~~Axial, Transverse~~	6.8	6.73-6.~~0~~66	6.6-4.7	6.6-6.1
	ligament of atlas	-	0.54-1.15	1.5-4.7	-
	Frontal arch of atlas	-	-	-	1.5-2.3
Direct stroke by the head	Axial	68	0.67-66.6	66-46.9	66-61
	Transverse ligament of atlas	-	5.4-11.5	15-47	-
	Frontal arch of atlas	-	-	-	15-23
Head stroke when falling down from the height equal to human height	Axial	95.2	94.2—92.4	92.4-65.6	92.4-85.4
	Atlas's transverse ligament	-	7.56-16.1	21-65.8	-
	Atlas's frontal arch	-	-	-	21-32.3
Head strike when falling down from 10 m height or higher	Axial	700	693-686	679-483	679-630
	Atlas's transverse ligament	-	56-119	154-490	-
	Atlas's frontal arch	-	-	-	154-238

Our biomechanical tests explain why,, when the 2nd cervical vertebra is undergoing the traumatic spandilolisthesis, there are possibilities for the axial injuries being open either towards the front or towards the rear. Yet, the decisive factor is the atlas inclination as against to the axis at the moment of the trauma.

It is worth drawing attention to the fact that an increase of the load on the atlas frontal arch up to 154 to 238 kg occurs only under the conditions when the drop of an object on the head from a significant height is combined with the rear head inclination which results in the atlas inclinations as against to the axis towards the rear which is accountable for the atlas dislocations connected with the tooth fracture. As mathematical calculations prove, the conditions for "explosive" fractures of the Jafferson type arise under significant axial loads when there no atlas inclination as against to the axial inclination.

It has already been determined that the action of the traumatic horizontal force transfers the load either onto the transverse ligament or the atlas frontal arch depending on its inclination in relation to the axis (Fig. 3a):

(1) at the moment of striking the head in the rear part when when the conditions of the atlas inclination towards the front exist, the traumatic force applied to the transverse ligament increase, that is $T = T_a - P_s'$; since $P_s' = -R$, than $T = T_a - (-R) = T_a + R$. At the moment of the same strike, when the atlas inclination is directed towards the rear, the traumatic force applied to the transverse ligament decreases: $T = T_a + P_s''$; since $P_s'' = -R$, then $T = T_a + (-R) = T_a - R$.

(2) when the head is hit under the conditions of the atlas frontal inclination, then the traumatic force applied to the transverse arch decreases $T = T_b + P_s'$; since $P_s' = -R$, then $T = T_b + (-R) = T_b - R$. When the same type of stroke occurs, but under the conditions of the atlas inclination towards the rear, the

traumatic force applied to the frontal arch increases: $T=T_b-P''_s$ then $P''_s=-R$, to $T=T_b-(-R)=T_b+R$.

The distribution of loads alon the 1st and 2nd cervical vertebras under the horizontal action of the traumatic force is presented in Table III

Table III. Loads distribution along the 1st and 2nd cervical vertebras when the traumatic horizontal force is acting (force is given in kg)

Rodzaj urazu 1	Siły obciążenia 2	Pochylenie kręgu szczytowego w stosunku do obrotowego 3			
		0°	fizjologiczne 5°–10° 4	ku przodowi 13°–24° 5	ku tyłowi 13°–45° 6
Warunki prawidłowe 7	Osiowa 8	6,8	6,73–6,66	6,6–6,1	6,6–4,7
	Więzadło poprzeczne kręgu szczytowego 9	-	0,54–1,15	1,5–4,7	—
	Łuk przedni kręgu szczytowego 10	—	—	—	1,5–2,3
Uderzenie od tyłu (w okolicę potyliczną) 11	Osiowa 12	6,8	6,73–6,66	6,6–6,1	6,6–4,7
	Więzadło poprzeczne kręgu szczytowego 13	68	67,4 66,8	69,5–70,3	66,5–63,3
	Łuk przedni kręgu szczytowego 14	—	—	—	—
Uderzenie z przodu (w okolicę czołową) 15	Osiowa 16	6,8	6,73–6,66	6,6–6,1	6,6–4,7
	Więzadło poprzeczne kręgu szczytowego 17	—	—	—	—
	Łuk przedni kręgu szczytowego 18	68	69,5 69,7	66,5–65,7	69,5–72,7

1- Type of trauma;

2- Loading forces;

3-Atlas inclination ~~as against~~ with respect to the axis;

4-Physiological;

5- towards the front;

6- towards the rear;

7- regular conditions;

8- Axial;

9- Atlas's transverse ligament

10- Atlas's frontal arch;

11-Rear strike (occiptal area);

12- Axial;

13- Atlas's transverse ligament

14- Atlas's frontal arch

15- frontal strike (forehead area);

16- Axial;

17- Atlas's transverse ligament;

18- Atlas's frontal arch;

The above-mentioned table indicates that the most dangerous thing resulting in the frontal interligament and intertooth dislocations is strokes in the head occiptal area, and the intertooth rear dislocations as a result of stroke in the head frontal area. The inclination of the atlas as against to the axis does not significantly affect the most loads of the transverse ligament and those of the frontal arch. This is the result of the magnitude of forces being decreased within the limits which do not exceed 5 kg.

In this way our biomechanical tests correspond to the results of the computations obtained when analyzing the clinical material and confirm the influence of the direction of the traumatic force and the atlas inclination as against to the axis on the type of injuries in this area.

The above discussed biomechanical characteristics should be taken into consideration when diagnosing and treating the injuries of the upper part of the neck's vertebral column. In case, if it is a chronic interligament dislocation, in order to determine the condition of the transverse ligament of the atlas under the functional X-ray examination, one ought to bring the chin closer to the thorax and thereby creating an additional pressure on the ligament.

When the strain, which is the result of the frontal or rear atlas dislocations, occurs, it is necessary from the biomechanical standview, to change the angle depending on the type of displacement. When the atlas inclination towards the fron takes place, the "itinerary" has to be directed at an angle open towards the rear; the "itinerary" angle is supposed to be open towards the front.

The patients with traumatic spandilolisthesis, the direction of the skeletal stretching should also be changed depending on the angles of the axis inclination as against to the 3rd cervical vertebra.

Thus, the application of mathematical methods to the examination of the upper cervical vertebra biomechanics allows to differentiate approaches to the analysis of injury types in this particular area as well as to the lay-out of appropriate treatment methods.

Fig.1. Biomechanics of the atlanto-occiptal and atlanto-axial joints on three perpendecular to each other planes: a- principal; b- axial, ~~and~~ c-horizontal.

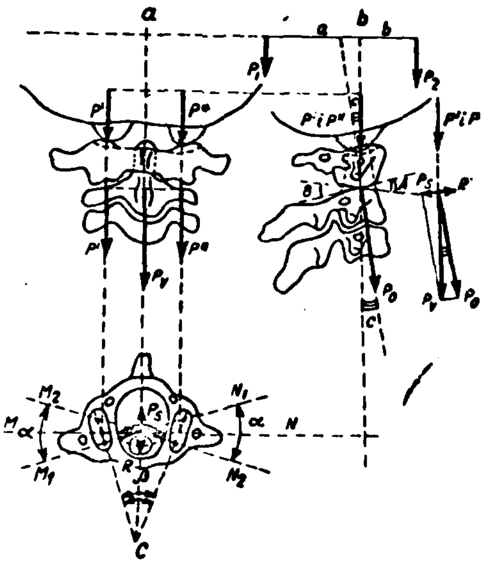


Fig.2. Biomechanics of the atlanto-occiptal and atlanto-axial joints on the axial plane under the atlas inclination as against to the axis: a- inclination towards the front; b- inclination towards the rear.

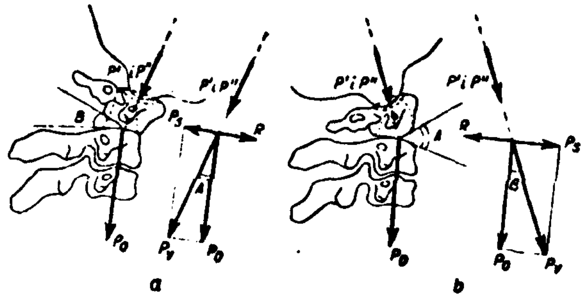
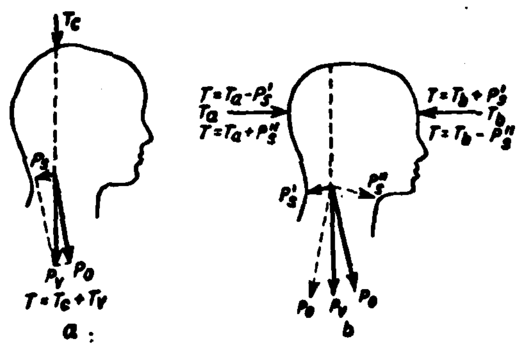


Fig.3. Biomechanics of the atlanto-occiptal and atlanto-axial joints under conditions of the traumatic force action: a- vertically; b- horizontally.



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